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What Do We Really Know about Mass Loss on the AGB?

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Abstract. Mass loss rate formulae are derived from observations or from suites of models. For theoretical models, the following have all been identified as factors greatly influencing the atmospheric structure and mass loss rates: Pulsation with piston amplitude scaling appropriately with stellar L ; dust nucleation and growth, with radiation pressure and grain-gas interactions and appropriate dependence on temperature and density; non-grey opacity with at least 51 frequency samples; non-LTE and departures from radiative equilibrium in the compressed and expanding flows; and non-equilibrium processes affecting the composition (grain formation; molecular chemistry). No one set of models yet includes all the factors known to be important. In fact, it is very difficult to construct a model that can simultaneously include these factors and be useful for computing spectra. Therefore, although theoretical model grids are needed to separate the effects of M, L, R and/or T_{eff} or Z on the mass loss rates, these models must be carefully checked against observations. Getting the right order of magnitude for the mass loss rate is only the first step in such a comparison, and is not sufficient to determine whether the mass loss formula is correct. However, there are observables that do test the validity of mass loss formulae as they depend directly on $d \log \dot{M} / d \log L$, $d \log \dot{M} / d \log R$, or $d \log \dot{M} / d \log P$.

1. Reducing the Mass Loss Formulae to $\dot{M}(L, M)$ along an Evolutionary Track

My analysis compares six published mass loss laws with the results of Bowen's 1995 model grid. Reimers' original formula (1975), was a fit of mass loss rate vs. LR/M using an assortment of stars for which mass loss measurements were available in 1975; the same collection of observations could have equally well been fitted as functions of R^2 or other combinations of parameters (Goldberg 1979). Vassiliadis and Wood (1993 = VW) fitted mass loss rates vs. period for pulsating AGB stars, mostly Miras. Van Loon et al. (2005) used data for supergiants. Wachter et al. (2002) based theirs on models for carbon stars. Schröder and Cuntz (2005) proposed a correction to the Reimers' formula based on some theoretical arguments. Blöcker (1995) proposed a modification to the Reimers' formula based on fitting models from Bowen (1988). Finally, the Bowen and Willson (BW) prescription is based on a 1995 grid of models that incorporated some essential features not found in any of the others, or Bowen (1988): Models followed the evolutionary tracks of individual stars, $R(L, M, \alpha, Z)$ where α is the mixing length parameter, and the driving amplitude of the "piston" boundary was regulated so that the peak power scales with stellar luminosity.

Mass loss rates are sensitive to stellar parameters L , R (or P or T_{eff}), and M . To compare them, we use the definition of effective temperature, $L = 4\pi R^2 \sigma T_{\text{eff}}^4$; a period-mass-radius relation $P(M, R)$; and an evolutionary track $R(L, M, \alpha, Z)$. This allows us to write all seven formulae as $\dot{M}(L, M)$ along a common set of evolutionary tracks.

2. Comparison with Observational Constraints

2.1. The Death-Line and the Death Zone

For each mass, $dM/dt = -(M/L_D)dL/dt$ defines the deathline luminosity L_D ; this yields critical mass loss rate $= (M/2 \times 10^6) M_{\odot}/\text{yr}$. Four of the relations (Reimers, SC, VW, and BW) have $(M = 1, \log L_D \approx 3.7)$ and $(M = 2, \log L_D \approx 4.0)$. The van Loon et al. relation would be close to an extension of this death zone to higher masses, but its slope is too shallow to match the lower mass stars. Wachter et al.'s carbon star mass loss rates have a relatively shallow slope and lower L_D , as does Blöcker's.

Figure 1 shows mass loss rates for Reimers', VW, and BW formulae, and the deathline for each case. It is clear that these two purely observational and quite independent empirical formulae agree substantially on the luminosity where the mass loss becomes important, although their $\dot{M}(L, M)$ are quite different. I conclude that we know the deathline quite well, at least for stars between 1 and 2 solar masses. The deathline satisfies $\dot{M}/M = \dot{L}/L$ and the death zone extends $\pm 1\text{dex}$ in mass loss rate above and below the deathline; the death zone's extent in $\log L$, and thus in time, is quite different for Reimers' formula compared with VW and BW.

2.2. The Exponents

Most tests of mass loss formulae have checked only whether they give the right order of magnitude of mass loss at the right range of stellar parameters. However, two other tests are potentially much more constraining and informative: Do they give the right $d \log \dot{M} / d \log L$ and the right $d \log \dot{M} / d \log M$? It is in these slopes that the various relations differ most. For shallow slopes, such as the Reimers', Wachter et al., and van Loon et al. examples, the mass loss occurs gradually as a star evolves up the AGB, so that by the time it reaches L_D it has already lost a significant fraction of its original mass. In contrast, the VW and BW formulae dictate that the mass is lost mostly near L_D . Slopes $d \log \dot{M} / d \log L$ and $d \log \dot{M} / d \log M$ in the vicinity of L_D for $M = 1$ and 2 are given for these seven formulae in Table 1, using on the Iben (1984) evolutionary tracks $R(L, M)$ and Ostlie and Cox (1986) $P(M, R)$.

The slopes may be compared directly with observational constraints. The slope $d \log \dot{M} / d \log L$ determines the amplitude of variation of the mass loss rate when the luminosity and/or radius of a star is varying, for example over a shell flash cycle. For the shell flash variation we could, in principle, use $L(t)$ and $R(t)$ from evolutionary models, but these show that a very good approximation is obtained by using just $L(t)$ and assuming the shell flash variation stays on the same evolutionary track. So $\Delta \log \dot{M} \approx (d \log \dot{M} / d \log L) \Delta \log L$; for a shell flash cycle $\Delta \log L \approx 0.4$. Observations (e.g. Olofsson et al 1990; Schöier, Lindqvist,

	R75	VW	B	W	SC	vL	BW
$d \log \dot{M} / d \log L$ for $M = 1$	1.68	15.2	4.4	3.1	0.77	1.26	1.43
$d \log \dot{M} / d \log L$ for $M = 2$	1	15.2	4.4	3.1	0.77	1.26	14.3
$d \log \dot{M} / d \log M$ for $M = 1$	1	~11	3.1	1.95	0	1.64	19.3
$d \log \dot{M} / d \log M$ for $M = 2$	1.31	~25	3.4	3.0	0.98	1.64	19.3

Table 1. Slopes from Seven Mass Loss Formulae: Reimers (1975), Vassiliadis and Wood (1993), Blöcker (1995), Wachter et al (2002), Schröder and Cuntz (2005), van Loon et al (2005), and Bowen and Willson (see Willson 2000, 2006).

and Olofsson 2005; Decin et al. 2006) suggest that the variation is at least 1 or 2 dex, a result consistent only with the VW observational result and the BW models of the seven formulae tested. There are significant secular and quasi-periodic variations in P for about 10 % of all Miras (Templeton et al 2005), an opportunity for further testing of the luminosity (or R or T_{eff}) dependence.

The slope $d \log \dot{M} / d \log M$ is harder to derive from observations, as it requires either that we know M for individual stars with measured \dot{M} or that we are able to fit a trend. The scatter of observations around the VW fit, about $\pm 1\text{dex}$, is an indication that $d \log \dot{M} / d \log L$ is large; if the range of masses included at a given P is taken from evolutionary tracks crossing the Mira period-luminosity relation (VW Figure 20), then the scatter in mass loss rate around the VW fit suggests $d \log \dot{M} / d \log M \geq 8$; however, both the numerator and the denominator are sensitive to observational error.

An observational quantity related to $d \log \dot{M} / d \log M$ is the duration of the mass loss phase. This may be defined as the time it takes the mass loss rate to increase by 2 dex near L_D , and we have used $\log L_D \pm 1\text{dex}$ for the death zone. For use with observational data, where M and hence L_D are not well known, the duration from $\log \dot{M} = -7$ to -5 will work equally well and give nearly the same answer. When there is substantial positive feedback between mass loss and mass loss rates, this shortens the duration of the mass loss phase substantially: For example, for the BW prescription with $d \log \dot{M} / d \log M$ artificially set to zero we get a duration (from 10^{-7} to $10^{-5} M_{\odot}/\text{yr}$) of 3×10^5 years while for the full BW prescription this is 1×10^5 years. Observations - for example, the width of the Mira $P - L$ relationship - suggest that the actual duration is no more than 200,000 years.

Ultimately, the strongest test of mass loss relations near L_D will be comparing the observed distribution of stars, $N(L)$, $N(P)$, or $N(T_{\text{eff}})$ with those obtained from evolution models using a well-chosen mass loss formula.

3. Conclusions

It is very difficult, perhaps impossible, to derive a mass loss prescription for use in stellar evolution directly from a set of mass loss observations, for the simple reason that measurable rates occur only for a narrow range of stellar parameters. Observational fits of AGB stars agree what those stellar parameters are, giving consistent deathlines $L_D(M)$. To determine the dependence of the

mass loss rates on stellar parameters for a given star as it evolves, we need to use models and indirect observational constraints. Thus we can constrain $d \log \dot{M} / d \log L$ at a given L using the amplitude of variation of the mass loss rate for a given $\Delta \log L$ or $\Delta \log P$, particularly near the deathline defined by $L_D = (M(dL/dt)/(dM/dt))$. We can also constrain $d \log \dot{M} / d \log M$, for a given $d \log \dot{M} / d \log L$, by the duration of the mass loss phase, or the width of the death zone. For currently available data, and using a standard set of evolutionary tracks, $d \log \dot{M} / d \log L \geq 14$; $d \log \dot{M} / d \log M$ is probably also greater than 10 and may be as large as 20.

For such large values of the exponents, their precise values only modify the shape of the corner in $\log M$ vs. $\log L$; the general pattern is the same. The mass remains essentially constant until the star reaches the deathzone, and then the envelope is removed in a short time. For population studies, all we really need to know is the deathline; a very good approximation for all mass loss formulae fitting the deduced sensitivity to L and M is that they evolve at constant mass to L_D and then their envelope disappears. The details of the mass loss formulae will still matter to those who wish to model the post-AGB phases or match the structure of the outflow as modulated by changes in L and M in the final stages, but for overall evolution of populations all that is needed is $L_D(M, Z)$, and this we know quite well, at least for $M \sim 1$ to $2 M_\odot$ and $Z \sim$ solar.

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Discussion

Busso: I would like to underline one more difficulty: when implementing an empirical formula into a code, you use your model estimates for the parameters, for example T_{eff} . Since T_{eff} is wrong in models due to lack of molecular opacities, you end up in using something which is actually meaningless!

Willson: Yes, thank you. I prefer to use L, M .

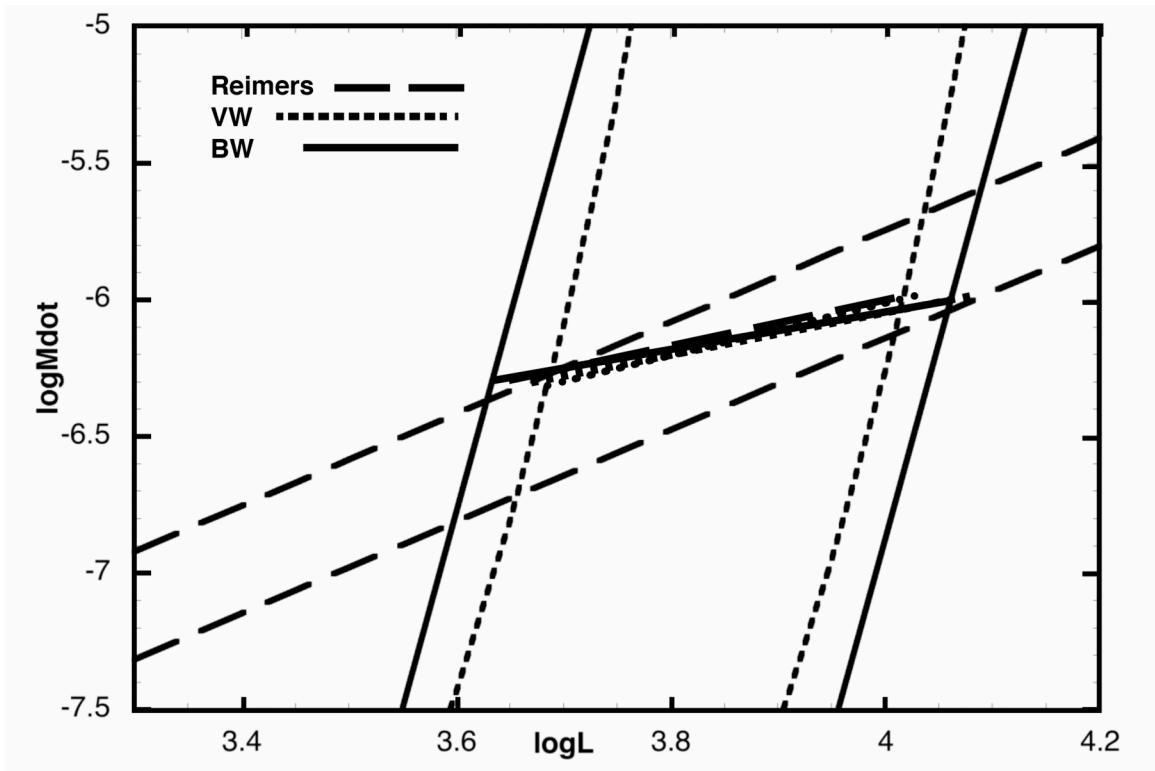


Figure 1: \dot{M} for $M=1$ and $M=2$ for three independent formulae: Observational fits by Reimers (1975), and Vassiliadis and Wood (1993), and model results by Bowen and Willson (see Willson 2000). Deathlines $1 \leq M \leq 2$ for all three relations largely coincide.